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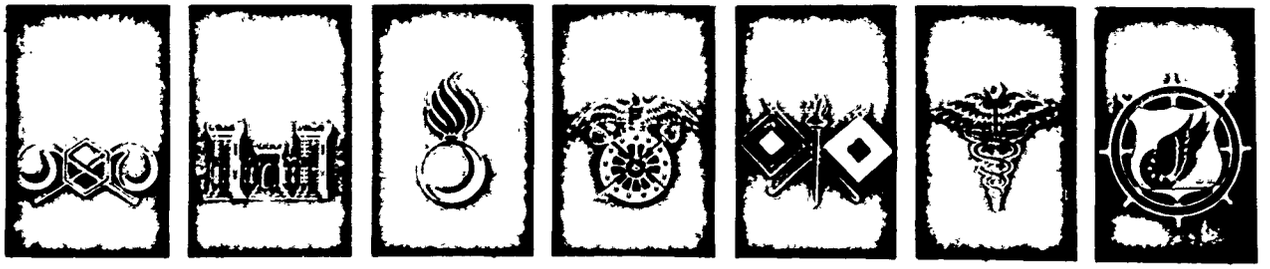

TITLE: Fast Response Solid State PME Detector for Laser Signals

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ABSTRACT: It is shown that the photomagnetoelectric effect in germanium can be used for building sensitive, fast response photodetectors if the following two conditions are fulfilled: (a) semiconductor slabs are made very thin and, (b) the front surface recombination velocity is made low. A germanium device, e.g. in which the sample is placed between the poles of a small permanent magnet produces output voltages of 200 mv with response times of below 10-7 seconds at high light intensities. The thin Ge wafers used in this device were obtained by controlled photoetching of single crystals to a thickness down to 6 microns whereby the current leads for the etching are arranged in such a way that they serve later as PME leads. The characteristics of the cell are presented in detail and show a voltage sensitivity almost independent of the light wavelengths from the visible to up to 1.7 microns as well as its dependence on the incident light intensity and the temperature. Since the device does not contain junctions, only thermal noise is present. Preliminary tests with PME cells which are photovoltaic and therefore do not need any power supply, reproduced the fine structure of ruby laser signals with a similar resolution as photomultiplier tubes. The ultimate limit of the response time of the device has not been determined, but is believed to be in the nanosecond range, making it possible to use the detector as demodulater in high volume optical communication systems.

FAST RESPONSE SOLID STATE PME DETECTOR FOR LASER SIGNALS

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I. Need for New Concepts in Fast Light Detectors

The invention of the optical maser (laser) by Maiman[1] in 1960 has provided us with a strong coherent light source that may be used as the carrier in wideband optical frequency transmission systems. The advantage of transmitting high volume information by means of modulated light is of particular significance for use over large distances in outer space.

An optical communication system consists, in principle, of three separate parts, i.e. (a) the light source, (b) the light modulator, and (c) the light demodulator. Considerable progress has been made recently in the development of CW optical lasers[2] and of light modulators[3] that are capable of operating up to the microwave region at reasonable power levels. The detection and demodulation of UHF and microwave modulated light, on the other hand, is still less satisfactorily solved. Photomultiplier tubes, e.g. that are frequently used as laser detectors, are seriously limited in their frequency response by their anode-dynode (and ground) output capacity and high anode resistances. It appears that even the best PM tubes cannot operate at frequencies above 10 mc without shunting out their output impedance and sacrificing some responsitivity. Furthermore, photomultipliers possess sharp response peaks in the visible and become very insensitive at the frequency of infrared lasers, (1.2 μ for the He-Ne laser). Therefore, new approaches of fast response light detection have to be explored.

The following solid state light detector, based on the photomagnetoelectric effect in germanium, was developed as part of the internal program at the Solid State and Frequency Control Division, USASRDL, Fort Monmouth, New Jersey, and is capable of overcoming some of the difficulties encountered with photomultipliers.

II. Operating Principle of the PME Detector

a. Description of the PME Effect

The photomagnetoelectric (PME) effect is defined as the voltage produced by incident light on a sample in the presence of a magnetic field, (Fig. 1).

$$U_{PME} = M\ H\ \Theta\ L \qquad \text{(Eq. 1)}$$

where H is the magnetic field strengths, Θ the incident light intensity and L the distance between the electrodes. The PME coefficient, M, is a materials property and is dependent on the front and back surface conditions and may also vary with the wavelength of the incident light. Furthermore, at high magnetic fields and light intensities, M is expected to be dependent on H and Θ. Since the PME voltage is a function of the product of light intensity times magnetic field, PME devices may be designed to measure either magnetic fields[4] or light intensities [5,6] by leaving the other parameter constant. For both types of applications, high sensitivities are achieved only with devices having high values of the PME coefficient, M. For the following we shall be concerned only with the application of the PME effect for the fabrication of a sensitive, fast response light detector.

b. Methods for Optimizing the PME Coefficient

Procedures of achieving high PME coefficients of fast response times may be derived from the physical interpretation of the PME effect. Fig. 2 shows the cross section of a PME sample. Carrier pairs are generated by incident light at the front surface of the semiconductor and diffuse in the direction of the back surface until they recombine. For sample thicknesses smaller than the diffusion lengths (order of 1 mm) most carriers recombine at the back surface. If, on the other hand, a magnetic field is applied perpendicular to the diffusion vector, the charge carriers are separated and establish an electric field perpendicular to the diffusion and magnetic field vectors.

A number of theories[7,8] for specialized cases of the PME effect have been advanced recently,* particularly for thick samples. None of these theories, however, permits a quantitative prediction of the size of the effect for the following reasons:

(1) M depends very strongly on the front surface recombination velocity, S_f, and for thin samples also on the back

*For a comprehensive list of literature on the PME effect see reference 5.

surface recombination velocity, S_b, and no independent method exists at present to obtain numerical values for these quantities. Variations in S_f influence the PME so strongly that, e.g. slight mechanical wiping of the surface with a tissue decreases the effect by several orders of magnitude. In other materials, e.g. Silicon, S_f is believed so large that no measurable PME effect exists.

(2) All previous theories are made with simplifying assumptions implying, e.g. that the concentration of optically generated carriers be small compared to the dark carrier concentration. Furthermore, the influence of the surface states is neglected. These conditions are - especially for thin samples and high light intensitites - not likely fulfilled.(9)

(3) It appears uncertain how far the present diffusion theory is still applicable in cases where the sample thickness is much smaller than the diffusion lengths. It was, therefore, decided to attempt instead an empirical procedure for achieving high PME voltages. This approach is based on the following considerations:

The PME field (Fig. 2) produced across the sample may be regarded as the sum of the Hall rotations of a longitudinal field (Dember field), established between the front and back surfaces for both types of carriers. Seeking high PME voltages at a given magnetic field strengths is therefore equivalent to seeking high Dember fields in the crystal. Now, Dember fields are the result of a carrier concentration gradient between the low recombination front surface and the high recombination back surface and high PME effects are therefore ultimately obtained by achieving high carrier concentration gradients between the front and the back of the sample. This can be done simultaneously in two ways:

(1) Increasing the concentration difference by careful chemical cleaning of the front surface and mechanical sanding of the back surface.

(2) Increasing the gradient by decreasing the distance between the front and back, i.e. decreasing the sample thickness.

While the first method is widely known and frequently applied, the effect of a decrease in sample thickness on the PME output voltage is usually underestimated. However, thick samples (1-2 mm) do not produce higher PME fields than 12 mv/cm at 9 kgauss and strong light intensitites, even with very clean surfaces, while thin samples of 20 microns thickness under the same light intensities and field strengths were found to produce PME fields of almost

1 v/cm. It is obvious that procedure (2) will only be valid to some optimum thickness w_{opt} below which the effect will decrease with the thickness. The size of w_{opt} depends both on the surface recombination velocities S_f and S_b and the absorption depths of the light and therefore can hardly be theoretically predicted. Since the surface recombination velocities S_f and S_b cannot be reproduced accurately in subsequent etchings of the same sample, it is not possible at present to measure the PME effect as a function of sample thickness alone and the experimental determination of w_{opt} is therefore difficult. However, in our experiments there appeared to be a steady trend of increasing PME voltage with decreasing thickness down to 10 microns thickness, indicating that w_{opt} must be below that value.

In addition to increasing the PME effect, this decrease in sample thickness has also the effect of shortening its response time, τ . There are two reasons for this:

(1) By increasing concentration gradient between front and back surface the diffusion velocity increases.

(2) By decreasing distance between front and back surface the effective diffusion path decreases.

Hence, one expects that the response time of the PME effect will decrease approximately with the square of the thickness w. A sharp decrease in τ with the sample thickness is observed experimentally. In thick samples (1 mm) we have found PME response times of between 20 and 100 μsec. Thin samples of 20 microns thickness of the same material, on the other hand, showed response times of well below one microsecond.

III. Fabrication of the PME Detector

a. Choice of Materials

PME voltages higher than one millivolt so far have only been observed in germanium and indium antimonide. However, since the controlled photoetching technique as a convenient means of obtaining single crystalline films is at present only known for n-type germanium, only this material was considered for the present application. Furthermore, the PME effect in germanium is higher than in InSb in the visible and near infrared, and this spectral range was of greater interest to us in view of laser application. The PME effect in InSb on the other hand, is most sensitive in the infrared up to 7.6 microns light wavelengths, and InSb has therefore been proposed for infrared PME detectors.[5,6]

The selection of materials was also determined by the desire to operate the device at room temperature and make it

as temperature insensitive as possible. The PME output voltage in germanium as a function of temperature has been previously investigated by Goldstein, Mette and Gärtner,[10] who found that the effect for both types of carriers possesses a maximum that shifts toward higher temperatures with increasing resistivity. This maximum will have its position at room temperature for 20-30 ohm cm material. N-type germanium in this range was therefore chosen as the best starting material for the fabrication of the detector.

b. Photoetching of Thin Ge Films

The preparation of thin n-type germanium films by controlled photoetching has been previously described.[11,12,13,14] The automatic thickness control achieved by this method is based on the findings that electrolytical etching of n-type germanium in alkaline solution occurs preferred at the thicker portions of the crystal if penetrating light (of a wavelength near the absorption edge) is irradiated into the crystal and produces holes that migrate to the surface.

Before etching, the samples were cut to slabs of 1 x .5 cm^2 area and lapped to five to seven mil thickness. Two copper leads were attached to the short ends of the sample, the contacts checked for ohmic resistance and the sample then mounted with alkali resistant plastic base wax on a 1" x 1/2" square glass or lucite slide, (Fig. 3). The use of two separate current leads to the anode not only provides a more even distribution of the etching current over the sample, but these leads serve later as the PME leads to the very thin and fragile crystal to which application of leads afterwards would be very difficult.

With this arrangement we were able to obtain quite satisfactorily mounted PME samples down to 6 micron thickness, but in most of the later cells 10-20 micron samples were preferred for their greater mechanical strengths.

c. Chemical After Etching of the Front Surface

After completion of the photoetching process the samples were taken from the electrolyte bath and thoroughly rinsed with distilled water. If the sample then is placed between the poles of a magnet it will already produce a rather high PME voltage upon illumination. However, it was found that this PME output can be further enhanced by 50% or more by cleaning the surface with a chemical after etching in slightly diluted CP4. The back surface during this process as in the photoetching remains coated with wax and therefore maintains the desired high back surface recombination velocity.

The chemical etching of the .5 cm^2 surface of a

sample which is only 20 microns or less thick, is difficult and requires special precautions since the etching tends to "bite" into the sample from the side or break through in spots, causing etch pits or holes. Good results were finally obtained in an arrangement whereby a small amount of etching solution was periodically released upon the surface of the sample and rinsed away after 1/2 second each time by dipping the cell in distilled water.

d. Mounting of the Cell

The PME cell is now ready to be placed in a magnetic field. In electromagnets of 10 kgauss field PME voltages of up to 1 volt are obtained with strong light intensities, and 1 cm electrode distance. Smaller and more portable units may be obtained by placing the cell between the poles of a small permanent magnet, (Fig. 4). Since high field strengths are of greater significance for obtaining high PME voltages than good homogeneity, a small Arnold C-magnet was chosen with tapering pole pieces that concentrate the field near the sample. The total unit weighs four ounces and operates with an effective field strength of 2500 gauss across an air cap of .7 mm. Since this same field strength can be obtained with smaller magnets in narrower gaps, and the PME voltage depends only on the length, but not on the width of the sample, it is possible to obtain even smaller units having the same voltage sensitivity, the only difference being a higher cell resistance of the smaller unit.

If the cell is to be used at low light intensitites, the leads should be twisted so as to minimize external pickup.

IV. Photoelectric Characteristics of the PME Cell

a. Spectral Response

According to the theory by Van Roesbroeck,[7] the ratio photoconductivity/PME effect should be independent of the light wavelength and can be used to calculate the carrier lifetimes. One notable exception, however, was predicted theoretically by Gärtner[8] and observed experimentally by Brand, Baker and Mette[15] near the absorption edge in germanium, where at low back surface and high front surface recombination velocities this ratio becomes dependent on the wavelength and may even reach negative values.

In the present detector, however, we are using only highly etched front surfaces and, therefore, obtain only positive values of the PME effect. The response of a typical PME detector is plotted in Fig. 5 as a function of the incident light wavelengths. Except for a steep increase near the absorption edge near 1.7 microns, the response is found to vary only very little from there to the blue part of the visible region. This behavior is in good agreement with the spectral response of the photoconductivity reported by Briggs.[16]

b. Temperature and Time Dependence

Previous measurements of the temperature dependence of the PME effect in this laboratory[10] have shown that the effect is very low at high and low temperatures but that a broad sensitivity maximum exists at intermediate temperatures, the exact position of which depends on the sample resistivity. For 25 ohm cm material this maximum occurs at room temperature and the change in the PME effect here is smaller than one percent per degree within a $\pm$ 10°C change.

In contract to this temperature change in the output voltage, the sensitivity of the cell decays initially irreversibly with time, probably by oxidation of the front surface. This decrease may amount to as much as 20 to 30 percent within 12 hours after the chemical etching has been applied, but the cell sensitivity then remains unchanged provided the surface is not mechanically or chemically affected. Still better time stability of the surface is achieved by enclosing the cell in a vacuum tube.

c. Sensitivity vs Light Intensity

In Fig. 6 is a plot of the output voltage three cells having different surface reoombination velocities, as a function of the light intensity. The light source used was a standard lamp calibrated for 2870°K color temperature. The light intensity in milliwatts/cm^2 refers to the total spectrum of the lamp and no attempt was made to correlate these numbers with the spectral distribution of the cell. However, since the spectral response is almost constant up to 1.7 microns wavelengths, the correction introduced by the spectral conversion is small. As may be seen from Fig. 8, the voltage output of the cells increase almost linearily up to light intensities of five to 50 milliwatts/cm, however, the linear range is larger for cells with less sensitive surfaces than for sensitive (low recombination) surfaces. Two types of cells may, therefore be designed: (1) for the measurement of small light intensitites, the front surface recombination velocity should be as small as possible, but the linear range then is not very large; (2) if the front surface velocity is less sensitive, the cell is better suited for high light intensity applications due to their extended linear range. However, in either case, the voltage will saturate at very high light intensities and the cells, therefore, are not destroyed by overexposure.

All the measurements were made in effective magnetic field strengths of 2500 gauss. By using higher field strengths, the sensitivity of the cells will increase at a rate indicated in Section g.

d. Response Time

Fig. 7 shows the oscillograph tracing of the light pulse of an ILA light flasher, Model SC 4 with a time resolution of .1 μsec/div. The curve is believed to approximate closely the true shape of the light pulse. One notices, in particular, a very fast rise time of the order 10^{-8} seconds, indicating that the response time of the sample must be faster than 100 millimicro-seconds with its exact lower limit not yet determined. The pulse hight of the curve is 200 *mV*.

e. Internal Resistance and Capacitance

An unique feature of the PME cell is that its impedance is almost independent of the incident light intensity. Only at very high light intensities does the cell resistance decrease by as much as 20 to 30 percent. The cell therefore, is particularly useful in combination with an amplifier circuit that requires constant impedance. The resistances of most cells used in the previous experiments were between one and two kilohms depending on the resistivity of the material used and the cell dimensions.

Since the cell does not possess p-n junctions, its capacitance is very small and caused mainly by the lead wires. By choosing proper lead dimensions, it may be kept below one μμf.

f. Noise

Two major sources of noise must be considered for the PME detector: (1) thermal (or Johnson) noise and (2) shot noise due to the statistical generation and recombination of carrier pairs. The shot noise in a PME sample is expected to depend on both front and back surface recombination velocities for which, as pointed out in Section II, no numerical values may be predicted. However, in contrast to junction type photocells, the PME cell has no dark current and its internal resistance does not change with decreasing light intensity. The shot noise, therefore, will diminish with decreasing light intensity, and therefore Johnson noise rather than shot noise will consititute the lower limit for the detection of weak signals. To test this assumption, a cell of 1 kilohm output resistance was connected to the input of a very low noise Hamner N-357 preamplifier and illuminated with weak dc light. The noise of the cell could not be distinguished from the amplifier noise which amounted to about five microvolts. This compares favorably to the Johnson noise which at room temperature, and for 1 mc bandwidth, is calculated to be 4 microvolts. Low noise therefore is one of the outstanding features that will enable the cell together with a low noise amplifier to detect very weak light signals.

g. Magnetic Field Dependence

The magnetic field dependence of the cell was measured and it was found that below 5000 gauss the PME voltage increases with the field linearily: above this point a slight saturation begins to appear until its deviation from linearity reaches 20 percent at 12k gauss. This behavior is in agreement with other magnetoelectric effects such as the Nernst effect[17] in germanium where deviation from linearity begins in the same range.

V. Applications of the Cell, and Conclusions

Table I, (Fig. 11) gives a survey on the most important features of the cell. The size of the PME effect for germanium

TABLE I — Properties of PME Cell

Sensitivity:	2.4 mv/mw/cm^2 at 2500 gauss
Spectral Response:	0.4.....1.8 microns
Temperature Dependence:	$<$ 1% per °C at 25° ± 10°C
Magnetic Field Dependence:	Linear to 5k gauss; 20% Deviation at 12k gauss
Response for Delay Time:	$<$ .1 μsec
Internal Resistance:	1kΩ
Capicitance:	$<$1 μμf
Overload:	Completely overexposure proof
Noise:	$<$ 5 μV at 25°C and f = 1 mc
Weight:	4 oz. including magnet

FIG. 11. TABLE OF PROPERTIES FOR PME DETECTOR

reported here is substantially higher than ever reported before in literature. This increased PME sensitivity enables the cell to serve as a sensitive fast response light detector for such spectral ranges where the responsitivity of photomultipliers becomes poor. As an example, Fig. 8 shows the oscilloscope tracing of a ruby laser signal taken at 1 μsec/cm time resolution with a portable cell. The spikes of the laser signal appear similar to graphs taken previously by other authors[1] with a photomultiplier tube. It shall be further noted that although the response time limits of the PME cell have not been investigated as yet in detail; there is nevertheless reason to believe that, using thinner samples, the response time of PME cells may be decreased below that achieved presently in photomultiplier tubes.

Sill unexplored, but possible in principle, are applications based on the simultaneous change of both the light intensity and the magnetic field. Examples of such devices could include choppers, mixers of electrical and optical signals and modulators.

In conclusion it has been shown that PME devices of considerable sensitivity, and with fast response times can be fabricated and used as fast response demodulators of modulated light pulses and as detector for the investigation of the fine structure of laser signals.

VI. References

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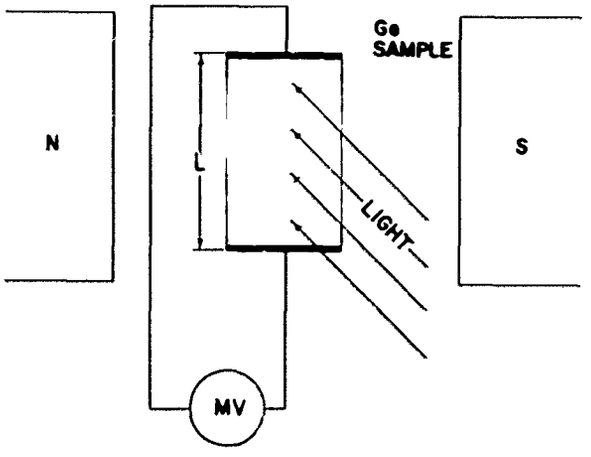


$U_{PME} = M \cdot H \cdot \Theta \cdot L$

M = PME COEFFICIENT H = MAGNETIC FIELD STRENGTH
$\ominus$ = LIGHT INTENSITY L = DISTANCE BETWEEN ELECTRODES

FIG.1. DEFINITION OF THE PME EFFECT

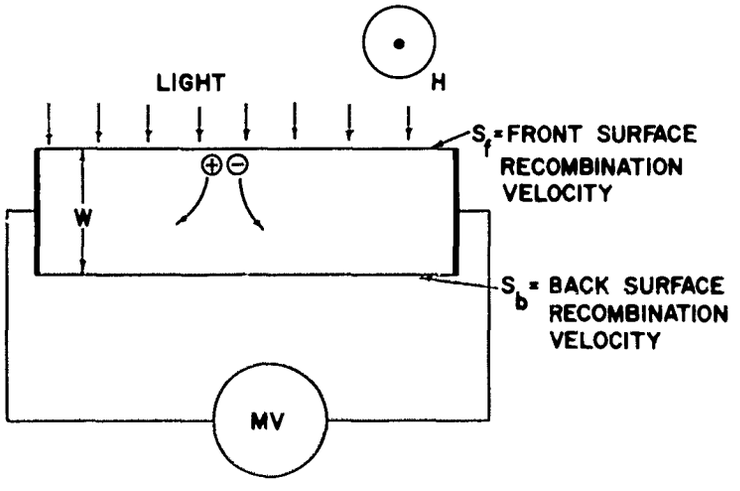


FIG. 2 : PHYSICAL INTERPRETATION OF THE PME EFFECT

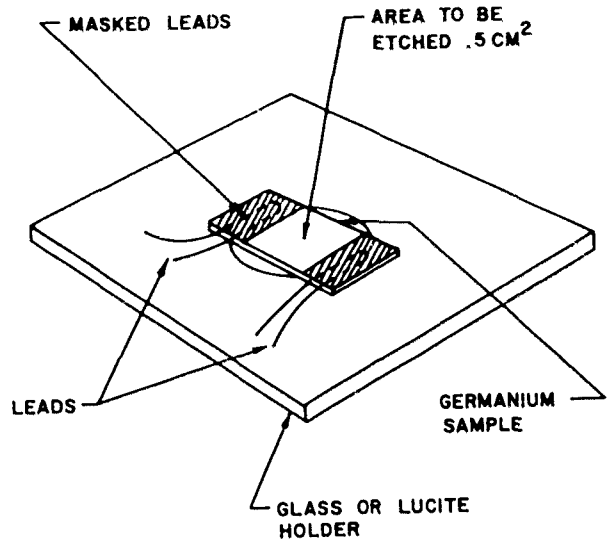
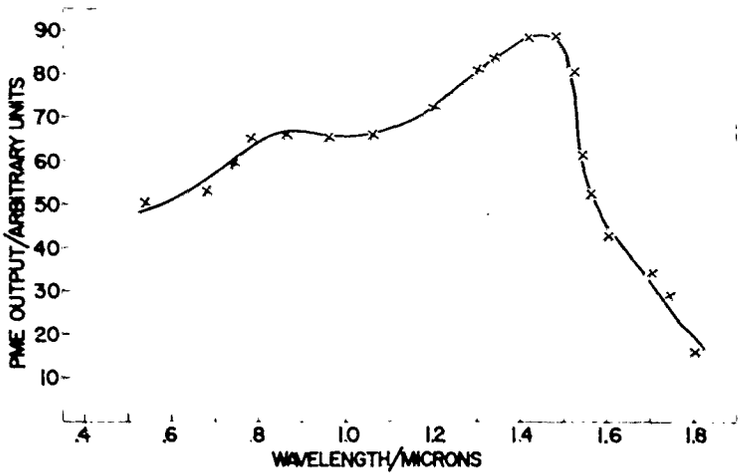


FIG.3. MOUNTING OF PME CELL

FIG. 4 PHOTOGRAPH OF PME CELL



SPECTRAL RESPONSE OF THE PME DETECTOR
FIG. 5

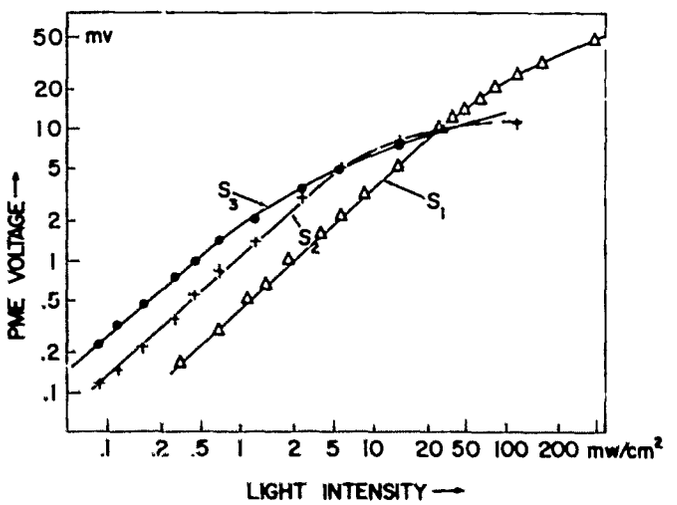


FIG.6. OUTPUT VOLTAGE vs. LIGHT INTENSITY FOR PME DETECTOR WITH S_1=HIGH, S_2=MEDIUM AND S_3=LOW SURFACE RECOMBINATION VELOCITY

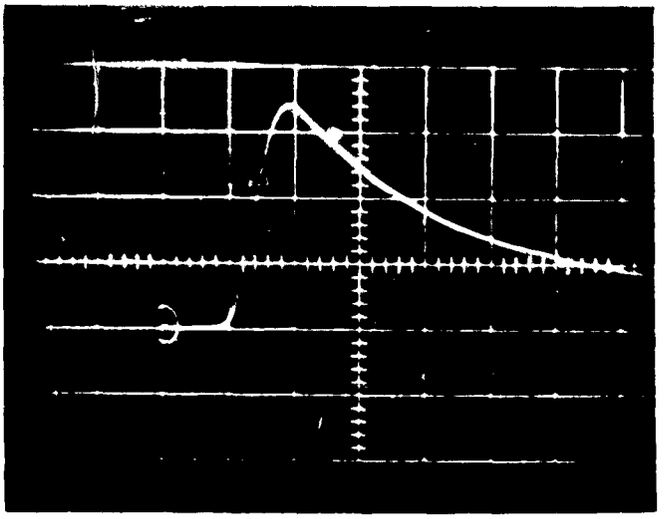


FIG. 7. .1 MICROSECOND LIGHT PULSE TAKEN WITH PME CELL - TIME SCALE .1 MICROSECOND/CM

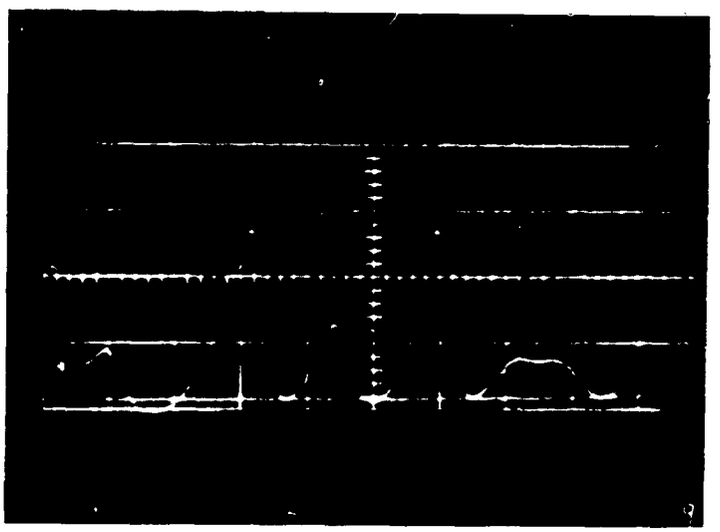


FIG. 8. LASER SIGNAL TAKEN WITH PME CELL. TIME SCALE 1 MICROSECOND/CM